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Thermal insulation materials based on agricultural residual wheat straw and corn husk biomass, for application in sustainable buildings

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ABSTRACT

The high energy consumption in buildings is a major contributor to climate change and atmospheric pollution in south cities of Chile. In this context, insulation materials are a key factor to reduce the energy demand during the operational stage of a building. These materials are however commonly fabricated from petrochemicals with high energy consumption, causing significant detrimental effects on the environment during the production and discarding stage. Due these reasons, insulation materials based on natural fibers waste appear as an excellent alternative, due to abundant availability in south regions of Chile, potential low cost, low energy consumption during the production stage and high bio-degradation rate at the end of life. In this research, block type insulation based on wheat straw and corn husk residual fibers were developed. Taguchi method was applied to investigate the effect on thermal conductivity and density of four control factors in three levels, namely fiber length, boiling time; NaOH concentration and blending time; in a L-9 orthogonal array. Furthermore, flexural and compressive stress were determined and compared with expanded polystyrene block insulation. The results show thermal conductivity values were between 0.046 and 0.047 W/mK. In addition, flexural stress results were good compared to those of the standard expanded polystyrene type IX. Finally, optimum conditions of the process were determined to obtain a final block, which was morphologically analyzed using scanning electron microscopy (SEM), while the thermal behavior was studied by thermogravimetric analysis (TGA).

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1. Introduction

It has been proven that thermal insulation in buildings reduces losses by transmission, which decreases heating energy consumption [24,33,13,26,32,34]. Standard thermal which regulate the insulation of buildings were established in developed countries more than 30 years ago [28,40]. From the beginning, studies on thermal insulation were based on acquired experience and subsequently, theories, analysis methods and calculation procedures were implemented to determine the best insulation system to be used [9].

On the market of thermal insulation materials, the main products are synthetic [46,38], principally produced from fossil fuels, and because of their high demand, concern has grown in the last century due to the excessive use [10,39] and their probable depletion [16]. Therefore, thermal insulation in residential buildings continues been an important objective for the global agenda of sustainability and the care of environment and human life [2,19,29,30,35].

In south of Chile, due to the scarce or poor thermal insulation of homes, there is a high consumption of heating energy. Moreover, residential areas generate high levels of air pollution with particulate matter (due to the biomass use to heat the homes), which according to the World Health Organization brings about adverse effects in the health of people [36]; Ministry of Environment [31,47]. In this context, the use of natural fibers for the development of insulation materials has become an essential alternative in order to achieve a sustainable development with less environmental negative impacts [3,21,30]. In this way, the use of synthetic insulation probably will be avoided to maintain comfortable conditions in buildings [12,27,44,45]. On the other hand, development and production of insulation materials with natural fibers must not be in conflict with the planting and harvesting of crops, instead, it should be focused on the use of produced residual biomass [4].

In this work, two types of insulation materials were developed based on natural residual fibers which come from the agricultural sector and are found in great volumes in south of Chile. The two used are wheat straw (1,510,779 tons of residue at a national level for the period

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2013–2014) and corn husk (9727 ha of crops in the year 2014) [1,37]. These residues were characterized chemically to later develop prototypes and conduct them to physical and mechanical tests. The objective of these tests was to prove their functionality as insulation materials and in addition, compare their properties with the properties of expanded polystyrene (EPS), which is one of the standard materials on the insulation material market. Finally, an energy balance evaluation of the prototype based on these fibers was done.

2. Materials and methods

2.1. Materials

Wheat straw and corn husk fibers (Figs. 1 and 2) were collected in the agricultural area close to Temuco city. The samples were dried in an oven to eliminate the excess water and stored for further tests. Tests based on the current regulations for insulation materials were applied in order to compare the properties of two final insulation prototypes with the properties of EPS.

2.2. Chemical composition

The preparation of the samples and the analysis of the chemical components was carried out according to the TAPPI 2007 standard, where an analysis of humidity, ash content and content of cellulose, hemicellulose and lignin was made (TAPPI [43]).

2.3. Experimental design

Two prototypes were developed through the pulping method. To obtain this prototypes, an experimental design was carried out through a Taguchi L-9 orthogonal array [8]. The parameters were studied in three levels and the response variables were the thermal conductivity and density, which need meet the requirements to be able to replace to the expanded polystyrene. The purpose of the experimental design was to generate prototypes with the best content of each level evaluated to determine the response variables and achieve a characteristic value of thermal conductivity and density.

2.4. Thermal stability

Thermogravimetric (TGA) analysis was used to analyze the thermal stability of the fibers. The measurements were performed in a TGA/DSC STA6000, Perkin Elmer, EEUU. The purge gas was set at 40 ml/min and the gas used was nitrogen (N2) at 40 ml/min [23]. The mass of the sample was 10 ± 1mg, the temperature program used was as follows: a heating from 25-120°C at a rate of 50°C/min; then it was kept 3 min at 120°C. Heating from 120-950°C at a rate of 100°C/min. Cooling from 950-450°C at 100°C/min, the change from gas to oxygen is carried out at a flow of 40 ml/min. Heating from 450-800°C to 100°C/min and finally an isotherm of 3 min at 800°C.

2.5. Infrared spectroscopy analysis

The IR spectra of the samples were registered using an ATR FTIR equipment, model Cary 630 in the frequency range 4000 to 500 cm^1. The method used was the diamond attenuated total reflectance (ATR), which is the most common sample interface used in infrared spectroscopy [41].

2.6. Surface analysis

The morphological visualization of the fibers and prototypes was performed through scanning electron microscopy (SEM) with a VP-SEM SU 3500 microscope produced by Hitachi in Japan. The following conditions were required: magnification 40-100-200-500X (superficial cut) and 30–100-200-500X (cross-section), detector BSE, 10KeV, WD 12mm, 30Pa [17].

2.7. Thermal conductivity and density

The thermal conductivity of each sample was determined by using the transient line heat source method with the KD2Pro device manufactured by Decagon Devices, Inc. [18]. This equipment measures in intervals of 1 s during a heating and cooling cycle of 90 s. KD2 complies with the specifications of the IEEE 442–1981 and ASTM D5334–08 standards. The accuracy of these tests was ±0.01 W/(mK). A 10 min gap between analyses was used to ensure the stabilization of the sensor. Meanwhile, the density was determined by the geometric calculation that relates the mass and the volume of the samples.

2.8. Mechanical properties

For the flexural and compression stress test, the prototypes were prepared and tested in accordance with the standards established in the ASTM C203 05a (2012) regulation Standard Test Methods for Breaking Load and Flexural Properties of Block-Type Thermal Insulation (ASTM [6]) and the ASTM C165 07 regulation (2012) Standard Test Method for Measuring Compressive Properties of Thermal Insulations (ASTM Standard C165–07 [5]). The universal test equipment Instron model 3369 was used, which was equipped with a load cell of 50 kN. The standard conditions in the test room were 20 ± 1°C and 50 ± 5% of relative humidity.

2.9. Energy balance

For a first approach to more detailed analysis of the life cycle assessment, a mass-balance and energy inventory of the optimal prototypes was carried out. The balance was focused on the measurement of energy consumption of each of the equipment used for the manufacturing of a prototype, whose functional unit was $1m^2$ of insulation material, with a thickness that complied with a U value of 0.45 W/m^2. On the other hand, a building performance simulation of an average house of the market of $60m^2$ was carried out using the software Designbuilder v3.4.0.039. The house without thermal insulation was established as a baseline, then three scenarios were compared: [1] Only roof thermal insulation, [2] only walls thermal insulation and [3] roof and walls thermal insulation. The embodied energy of the thermal insulation material developed versus the saved energy due to the application of the materials was analyzed. Finally, considering the energy demand and an estimated sale price of the material an economic analysis was done.

3. Results and discussion

3.1. Chemical composition of fibers

According to the analysis performed to the residual biomass, it was noted that these fibers possessed high levels of α-cellulose, hemicellulose, and lignin; these levels were very similar to other material analyzed by Robert and Hurter [22], which are detailed in Table 1. The composition of both wheat straw and corn husk was similar to that presented by rice, bamboo, sugar and oat Straw. The high resistance and rigidity that these fibers possessed are highly associated with the lignin content.

3.2. Experimental design

According to the experimental design Taguchi, both fibers were determined to have a yield that was close to 50%. Fig. 3 shows the insulation prototypes obtained through the pulping method.

In Fig. 4 the analysis of the influence of the variables for thermal conductivity is shown, where the percentages correspond to the

contribution of said thermal conductivity. For wheat straw, thermal conductivity was dominated by fiber length with 59.5%, followed by blending time with 21.9%. On the other hand, corn husk was dominated by additive concentration with 42.3%, followed by blending time with 40.18%; therefore, in both cases two optimal prototypes were carried out, emphasizing the processes in the critical factors of each fiber.

The optimal results determined in the application of the experimental design are shown for each fiber studied in Table 2 where wheat straw used 4 cm. of length, 30 min of boiling, 1.5% additive concentration (NaOH) and 10 s of blending. Corn husk used 10 cm. of length, 45 min of boiling, 0.5% of additive concentration (NaOH) and 3 s of blending. Factors were utilized to develop the optimal prototypes of each fiber.

3.3. Thermal stability

The proximal analysis carried out to wheat straw in its natural state is detailed in Fig. 5. A loss of mass between 32 - 119°C in the sample was observed, corresponding to 6% associated with moisture. Subsequently, a greater loss ranging between 157 - 938°C was observed, which corresponded to 69% associated with volatile compounds where a 34% corresponds to α-cellulose and 35% corresponds to hemicellulose. Once the environmental change to oxygen took place, fixed carbon losses of 17% were observed and were between 477 - 663°C corresponding to lignin. Finally, the percentage of ashes was 3% and was subsequently displayed at 700°C.

In the analysis performed on the wheat straw prototype, a loss of mass between 49 - 119°C in the sample was observed, corresponding to 7% associated with moisture. Subsequently, a great decrease was observed, which ranged between 164 - 937°C, and corresponded to 78% associated with volatile compounds. Once the environmental change to oxygen took place, fixed carbon losses of 14% associated to lignin content were observed and were between 478 - 639°C. The percentage of ashes was 1% and was subsequently displayed at 700°C.

The proximal analysis of the corn husk fiber in its natural state is detailed in Fig. 6, where a loss of mass in the sample between 39 - 117°C was observed, corresponding to 5% associated with moisture. Subsequently, a greater loss ranging between 160 - 933°C was observed, which corresponded to 74% associated with volatile compounds where a 32% corresponds to α-cellulose and 42% corresponds to hemicellulose. Once the environmental change to oxygen took place, fixed carbon losses of 17% were observed and were between 475 - 687°C corresponding to lignin. Finally, the percentage of ashes was 1% and was subsequently displayed at 700°C.

In the analysis performed on the corn husk prototype, a loss of mass in the sample between 31 - 152°C was observed, corresponding to 7% associated with moisture. Subsequently, a greater loss ranging between 222 934°C was observed, which corresponded to 78% associated with volatile compounds. Once the environmental change to oxygen took place, fixed carbon losses of 15% associated to lignin content were observed and were between 480 - 556°C. The percentage of ashes was 1.5% and was subsequently displayed at 700°C.

Therefore, in accordance with this results, the natural residual biomass panel prototypes shown to be stable until 250°C, indicating that processing temperature of the material should be lower than this value to avoid thermal degradation. The same happens with the works of [12,14], where the first authors developed a material that shows a thermal stability of up to 300°C, after which begins to occur the degradation of the material, while the materials of the second authors presents a stability close to 350°C.

3.4. Infrared spectroscopy analysis

The main components of the fiber, α-cellulose, hemicellulose, and lignin were identified in the spectra and defined bands of the characteristic chemical group as shown in Fig. 7.

For the fiber wheat straw, an absorption band of around 3350 cm^{-1} corresponding to the O—H bond was observed, which represented a stretch vibration of α-cellulose and hydrogen bonds from the hydroxyl groups. The peak at 2750 cm^{-1} was the characteristic band of the C—H alkane, which had symmetric and asymmetric vibrations of α-cellulose tension. Both peaks were maintained for both fiber states although they were weaker after the pulping process.

For the prototype wheat straw, one of the most notable changes was found in the band 1200 cm^{-1} at 2200 cm^{-1} where the band 2200 cm^{-1} was associated with C═O stretching of carbonyl groups in hemicellulose, which became very weak in the insulation material prototype; this was mainly due to the elimination of the acetyl group present in the hemicellulose. This also took place with the bands and groups detected at 1800 cm^{-1} and 1500 cm^{-1}, which could be attributed to C—C and C—H respectively, due to the vibrations derived from lignin where the peak of 1500 cm^{-1} was weaker.

The spectra and bands of the corn husk fiber were identified, an absorption band around 3300 cm^{-1} corresponded to the O—H band, which represented a stretching vibration of α-cellulose and hydrogen bonds from the hydroxyl groups. The peak at 2800 cm^{-1} was the characteristic band of C—H alkane, which had symmetric and asymmetric vibrations of -cellulose tension. Both peaks were maintained for both fiber states.

For the prototype corn husk, one of the most notable changes was found in the band 1250 cm^{-1} at 2250 cm^{-1}, where the band 2250 cm^{-1} was associated with the C═0 stretching of carbonyl groups in hemicellulose, which decreased and became weaker in the insulation material prototype; this was primarily due to the solubilization of hemicellulose. The same process also took place with the bands and groups detected at 1750 cm^{-1} and 1500 cm^{-1}, which could be attributed to C—C and C—H due to the vibrations derived from lignin.

The interpretation of spectros are based on the document developed by [15], where the groups associated to each absorption band are indicated. In addition, our results are similar to the results of thermal insulation materials of lignocellulosic origin found by other authors [42,25].

3.5. Surface analysis

The microscopic analysis of the fibers and prototypes was carried out in two stages, the first for the material in its natural state and the second was for the processed material, that is to say, for the two optimal prototypes. The observations were carried out for the inner and outer surface of the samples; these images are shown in Fig. 8 (wheat straw) and Fig. 9 (corn husk) in which image a) and b) show the material in its natural state and image c) and d) show the processed material or in prototypes.

For wheat straw, the observation was made in images a) and b) that the fiber in its natural state possessed an internal and external structure of open porosity. The average size of the porous structure was around 10 μm. After the pulping process, this structure was maintained, in which small fibers with a great length-to-diameter ration could be observed (image c); this is considered very interesting from the point of view of the insulation materials. Image d shows that the fiber bound in a good manner, thereby achieving a good homogeneity of the material.

For corn husk, the observation was made in images a and b that the fiber, in its natural state, possessed a porous structure. The average size of its structure was approximately 50 μm. After the pulping process, this structure became much more closed. In image c, it can be observed that the fibers were compacted in an excellent manner. Image d) shows that the internal structure of the insulation prototype homogenized correctly.

3.6. Thermal conductivity and density

The thermal conductivity and density was measured for each prototype generated with the parameters optimum given by the experimental design of Taguchi, the average of each sample are detailed in Table 3.

The thermal conductivity value obtained for wheat straw was 0.046 ± 0.001 W/mK and for corn husk 0.047 ± 0.001 W/mK. These values were very similar to the values expanded polystyrene of 10 kg/m^3 [20], with thermal conductivity of was 0.043 W/mK. Moreover, the values were better than those obtained by other authors in hemp fibers [35]. Therefore, it can be said that the thermal conductivity of the prototypes is good and the material could be used to insulate buildings.

The results of density of the prototypes also are shown in Table 3. The values for wheat straw ranged from 104.84 and 112.50 kg/m^3 and for corn husk between 118.79 and 128.17 kg/m^3, values which were much higher than those of expanded polystyrene, which ranged from 10 to 30 kg/m^3. This could be considered a disadvantage; however, there are variables that must be evaluated in greater depth, such as thermal inertia, which might have natural insulation panels.

Moreover, it was reported that the moisture of the materials was on average 7.54% for wheat straw and 7.65% for corn husk, which indicated that they were in a dry state. Because of this, the risk of the prototypes generating some kind of pathogenic agent was minimized and the loss of their thermal insulation properties was avoided.

3.7. Mechanical properties

The mechanical properties for the optimal prototypes of wheat straw and corn husk were compared with those of expanded polystyrene (EPS) of a density of 25 kg/m^3, and whose properties are detailed in the regulation ASTM 578 Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation (ASTM [7]). Table 4 contains the summary of the properties.

Five samples were analyzed for the flexural test, with the purpose of characterizing the complete behavior throughout the material and assuring its homogeneity. Fig. 10 shows the bend test curves of the prototypes compared with EPS. Wheat straw reached 0.15 MPa, a value which was very close to that of EPS, which reached 0.20 MPa. Corn husk, on the other hand, reached 0.80 MPa, easily passing that of EPS. Therefore, it must be noted that the prototypes developed should display a good bending behavior when used in buildings.

Compression measurements of three prototypes of each fiber were taken with the objective of obtaining a reliable result and thus assuring the homogeneity of the material. Fig. 11 shows the curve of the material in the compression test compared to expanded polystyrene, which possessed a maximum value of 0.14 MPa. Wheat straw reached 0.057 MPa and corn husk 0.024 MPa, in which both values were easily passed by EPS, which could represent a disadvantage of the fibers. However, this is a variable that should be analyzed in greater detail to evaluate their assembly in homes.

According to the applied experimental design, the prototypes present mechanical properties very similar to those found by [12,42], where thermal insulation materials based on residual fibers shown a behavior similar to that of the residues evaluated in this work, where the properties of flexural stress exceed EPS, but compressive stress must be evaluated at greater depth to be applied to a wall element.

3.8. Energy balance

Table 5 shows the summary of the energy consumption of the production of the optimal prototypes of the fibers from where it can be extracted that in order to reach the transmittance value that complies with the Air Decontamination Plan (PDA), insulation with a thickness of 8.9 cm must be used for 1 m^2 of wheat straw panel. Through the current process studied, this meant using 9.41 k of fiber, in which the final energy consumption corresponded to 187.56kWh. On the other hand, insulation with a thickness of 9.1 cm had be used for 1 m^2 of corn husk panel, which involved using 11.24 k of fibers, in which the final energy consumption corresponded to 239.96kWh. The results of the energy simulation are shown in Table 6. The baseline energy demand was 16,204.70kWh/yr. In the scenarios 1, 2 and 3 the energy demand was around 25%, 70% and 82% less respectively. Therefore, considering the thermal insulation material developed considering the scenario 3 (for the dwelling with a wall surface of 101.46 m^2 and a roof surface of 30.76 m^2), the total embodied energy was 4799.18kWh for wheat straw and 31,727.51kWh for corn husks, results very similar to what was found by [11]. Finally, considering that the commercial price of the material would be approximately USD 5 per m^2, the energy balance shows that the investment would be recovered in the second year for the wheat straw material and in second and a half year for the corn husk, which is significant since generally the houses are projected with a lifespan of 50 years.

4. Conclusions

The thermal conductivity of the prototypes was close to 0.046 W/mK, a value which is directly comparable to others thermal insulation materials as expanded polystyrene with a density of 10 kg/m^3. Therefore, the fibers studied can be used for thermal insulation materials, which will contribute to the energy efficiency and thermal comfort in homes.

The life cycle inventory analysis for the manufacturing stages points out that the drying of prototypes uses an average of 65% of total energy consumption being the main process to optimize to take advantage of the fibers available in agricultural regions.

Finally, the embodied energy used in these materials for an average standard house, would be recovered in the second year for the wheat straw material and in second and a half year for the corn husk, being less than 5% of the lifespan of the building.

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